

# Neutrino masses and $0\nu\beta\beta$ from neutrino oscillations

Michele Maltoni

Instituto de Física Teórica UAM/CSIC

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*"Una manera de hacer Europa"*

## General three-neutrino oscillation framework

- Equation of motion: **6 parameters** (including **Dirac** and neglecting **Majorana** phases):

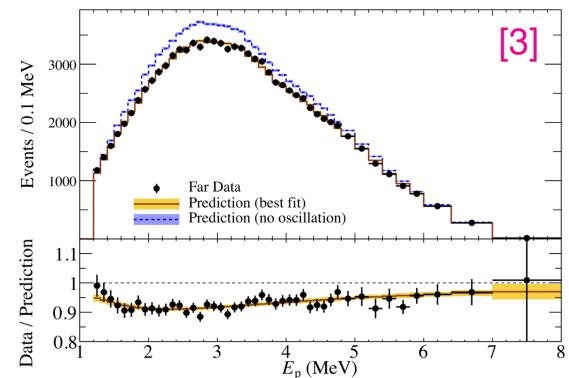
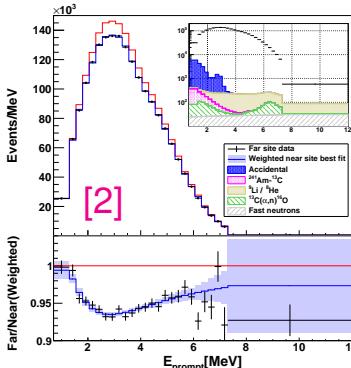
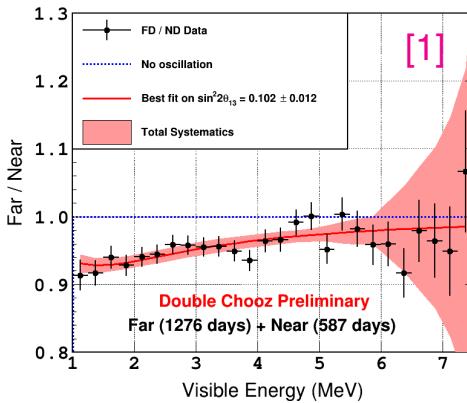
$$\begin{aligned}
 i\frac{d\vec{\nu}}{dt} &= H \vec{\nu}; \quad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^\dagger \pm V_{\text{mat}}; \\
 U_{\text{vac}} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}; \\
 D_{\text{vac}} &= \frac{1}{2E_\nu} \left[ \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) + \cancel{m_1^2} \right]; \quad V_{\text{mat}} = \sqrt{2} G_F N_e \text{diag}(1, 0, 0).
 \end{aligned}$$

**6 parameters**  $\iff$  **6 types of experiments**

- SOLAR** sector:  $\begin{cases} \text{solar experiments (mainly SNO)} & \rightarrow \theta_{12} \\ \text{reactor LBL (KamLAND)} & \rightarrow \Delta m_{21}^2 \end{cases}$
- REACT** sector:  $\begin{cases} \text{reactor MBL (Double-Chooz, Daya-Bay, Reno)} & \rightarrow \theta_{13} [\Delta m_{31}^2] \\ \text{atmospheric experiments (SK, DC)} & \rightarrow \theta_{23} \end{cases}$
- ATMOS** sector:  $\begin{cases} \text{accelerator LBL-DIS } \nu_\mu \rightarrow \nu_\mu \text{ (T2K, NOvA)} & \rightarrow \Delta m_{31}^2 [\theta_{23}] \\ \text{accelerator LBL-APP } \nu_\mu \rightarrow \nu_e \text{ (T2K, NOvA)} & \rightarrow \delta_{\text{CP}} \end{cases}$

## Reactor neutrino disappearance and $\theta_{13}$

- Positive  $\bar{\nu}_e$  disappearance signal in DOUBLE-CHOOZ [1], DAYA-BAY [2], RENO [3];
- experimental results are mutually consistent  $\Rightarrow$  it is now a firmly established fact that  $\theta_{13} \neq 0 \Rightarrow$  full  $3\nu$  oscillation phenomenology;
- all these experiments have spectral capabilities and detector units placed at different baselines  $\Rightarrow$  uncertainties in the reactor flux predictions do **not** affect the results.



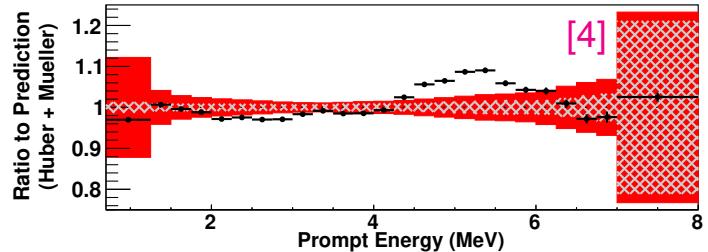
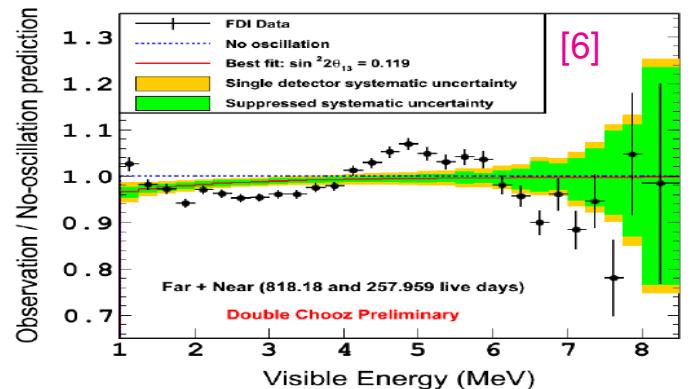
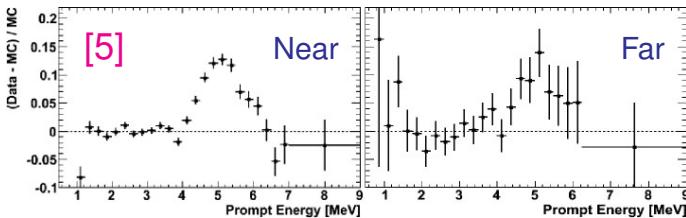
[1] T. Bezerra [DOUBLE-CHOOZ], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

[2] D. Adey *et al.* [DAYA BAY], Phys. Rev. Lett. **121** (2018) 241805 [[arXiv:1809.02261](https://arxiv.org/abs/1809.02261)].

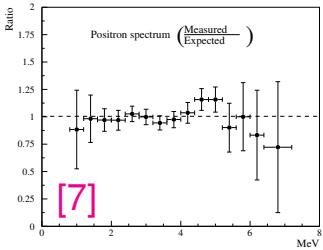
[3] J. Yoo [RENO], online talk presented at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

## Trouble with reactor fluxes

- Neutrino 2014: RENO [5] reported an **excess** of events around 5 MeV;
- excess (not deficit) & independent of  $L \Rightarrow$  **flux feature**, not **neutrino oscillations**;
- seen by Daya-Bay [4], Dbl-Chooz [6], and many others (also old Chooz [7]);
- $\Rightarrow$  reactor fluxes **not** properly understood.

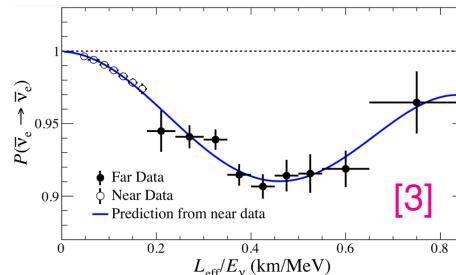
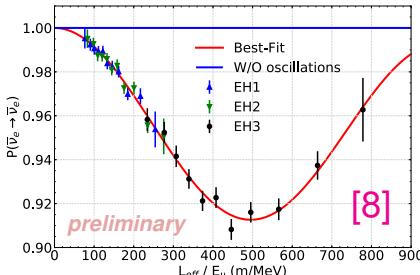


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- [4] F. P. An *et al.* [Daya-Bay], CPC **41** (2017) [[arXiv:1607.05378](https://arxiv.org/abs/1607.05378)].
- [5] S.H Seo [RENO], talk at Neutrino 2014, Boston, USA, June 2-7, 2014.
- [6] I.G. Botella [Double-Chooz], talk at EPS 2017, Venice, Italy.
- [7] M. Apollonio *et al.* [Chooz], PLB **466** (1999) 415 [[hep-ex/9907037](https://arxiv.org/abs/hep-ex/9907037)].



## Measuring $\theta_{13}$ and $\Delta m_{31}^2$ from reactor data

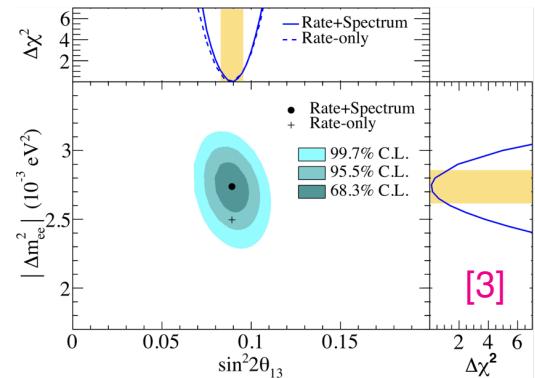
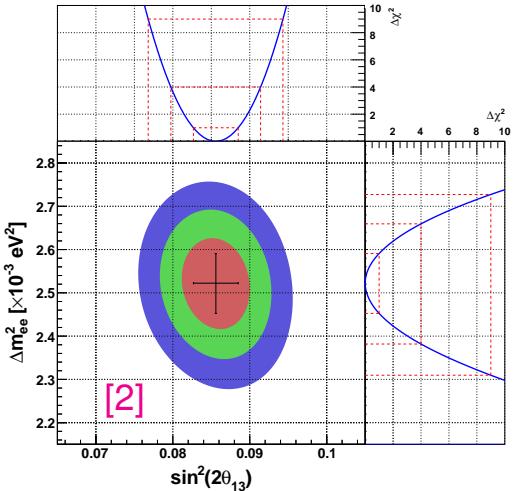
- Spectral information from Double-Chooz, Daya-Bay and Reno  $\Rightarrow$  oscillation pattern clearly visible  $\Rightarrow \theta_{13}$  and  $\Delta m_{31}^2$  accurately determined by reactor data;
- FAR/NEAR spectral ratio  $\Rightarrow$  flux shape irrelevant;
- accuracy from reactor  $\nu_e \rightarrow \nu_e$  comparable with LBL  $\nu_\mu \rightarrow \nu_\mu$ , but oscillation channel is different  $\Rightarrow$  important complementary information available.



[2] D. Adey et al. [DAYA-BAY], arXiv:1809.02261.

[3] J. Yoo [RENO], online talk at Neutrino 2020.

[8] J.P. Ochoa-Ricoux [DAYA-BAY], talk at Neutrino 2018.

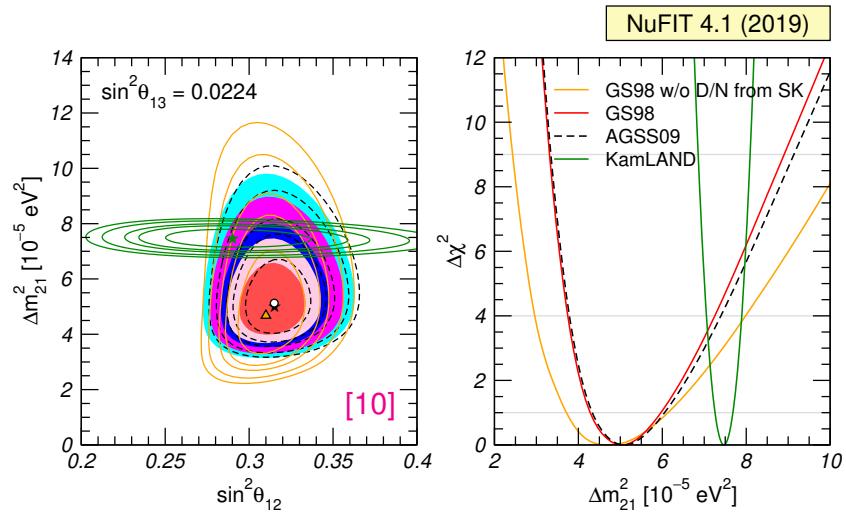


## Relevance of solar data in the determination of $\Delta m_{21}^2$ and $\theta_{12}$

- $P_{ee} = c_{13}^4 P_{\text{eff}} + s_{13}^4$ ,  $i \frac{d\vec{v}}{dt} = \left[ \frac{\Delta m_{21}^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} \right] \vec{v}$ ,  $\vec{v} = \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix}$ ;
  - $\nu_\mu \equiv \nu_\tau \Rightarrow$  no sensitivity to  $\theta_{23}$  and  $\delta_{\text{CP}}$ ;
  - $\Delta m_{31}^2 \approx \infty \Rightarrow$  specific  $\Delta m_{31}^2$  value irrelevant;
  - $\Rightarrow$  data only depend on  $\Delta m_{21}^2$ ,  $\theta_{12}$  and  $\theta_{13}$ ;
  - param's:  $\begin{cases} \theta_{12} \text{ dominated by SNO;} \\ \Delta m_{21}^2 \text{ dominated by KamLAND;} \end{cases}$
  - solar region determined by **high-E** data, **low-E** contribution marginal;
  - SNO-NC measurement confirms SSM;
  - KamLAND precisely determines the oscillation pattern.
-

## Tension between solar and KamLAND data

- A weak tension appears in the determination of  $\Delta m_{21}^2$  from solar and KamLAND data;
  - the choice of the assumed solar model (GS or AGSS) has little impact on the issue;
  - historically, it was noted that such tension was alleviated by a non-zero  $\theta_{13}$  value [9];
  - it is known that part of the problem arises from the large D/N asymmetry measured by SK, which favor lower  $\Delta m_{21}^2$  values than KamLAND;
  - another cause is the non-observation of a “turn-up” in SK and SNO lowest energy bins;
- ¿ troubles in the reactor spectrum  $\Rightarrow$  is KamLAND measurement reliable?



[9] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [[arXiv:0806.2649](https://arxiv.org/abs/0806.2649)].

[10] I. Esteban *et al.*, JHEP **01** (2019) 106 [[arXiv:1811.05487](https://arxiv.org/abs/1811.05487)] & NuFIT 4.1 [<http://www.nu-fit.org>].

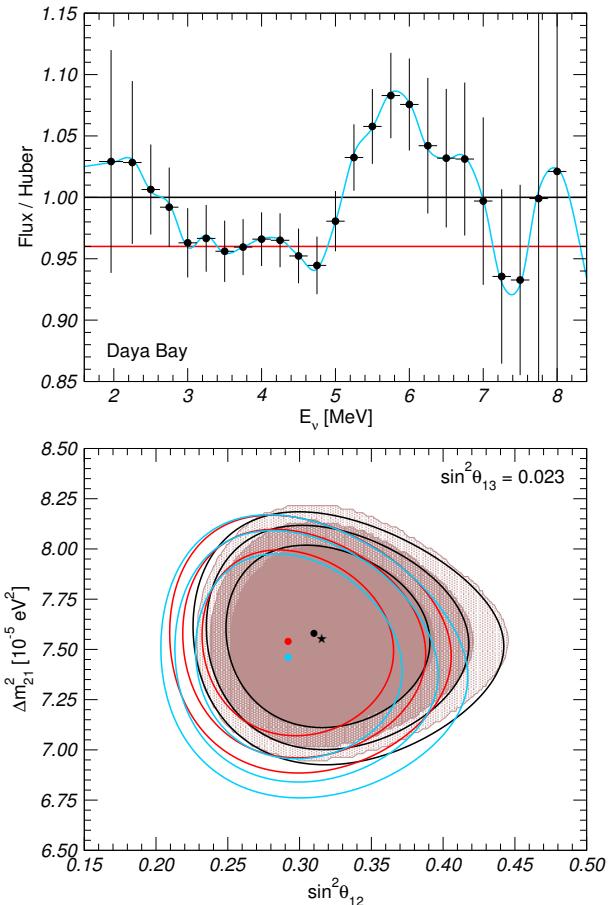
## KamLAND and reactor $\nu$ spectrum

- KamLAND detects neutrinos from various reactors, and has **no** near detector. Hence, spectral distortions may be potentially relevant;
- the effects of such distortions in KamLAND were discussed briefly in [11], and more in detail in [12]. In both cases the impact on  $\Delta m_{21}^2$  was found to be small;
- since 2017 we fix KamLAND reactor spectrum to the measured Daya-Bay  $\nu$  flux [4];
- ⇒ the determination of  $\Delta m_{21}^2$  is robust against reactor flux uncertainties, and does not help in reconciling **solar** and **KamLAND** data.

[4] F.P. An *et al.* [DAYA-BAY], arXiv:1607.05378.

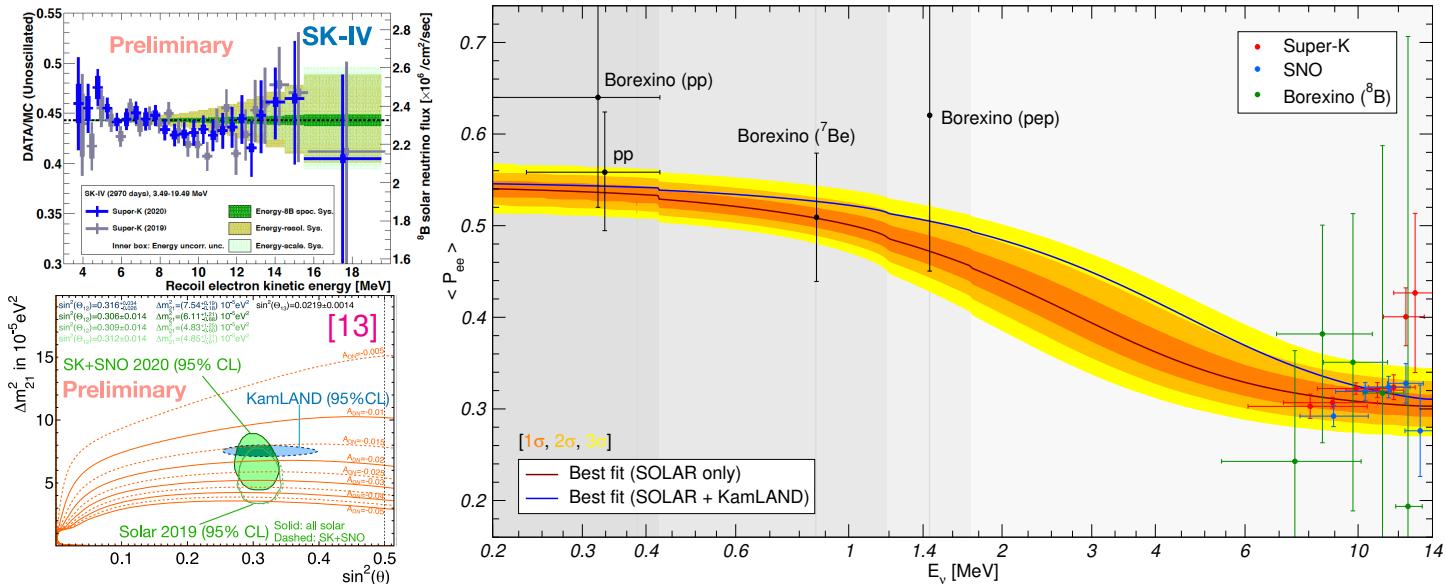
[11] M. Maltoni, A.Yu. Smirnov, arXiv:1507.05287.

[12] F. Capozzi *et al.*, arXiv:1601.07777.



## Transition between vacuum and MSW regime in solar data

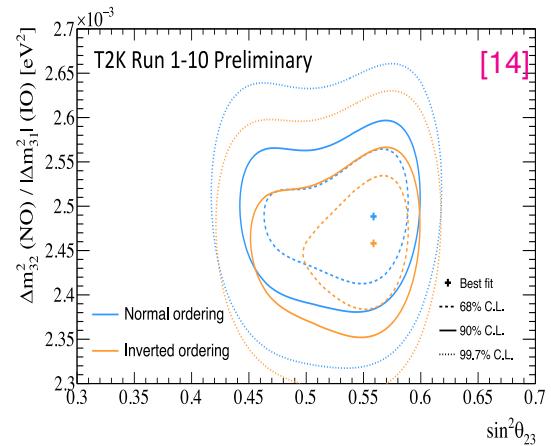
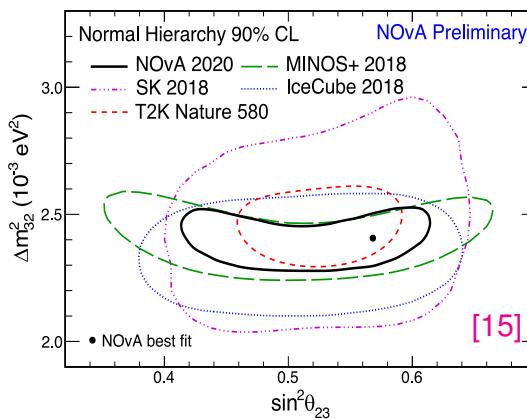
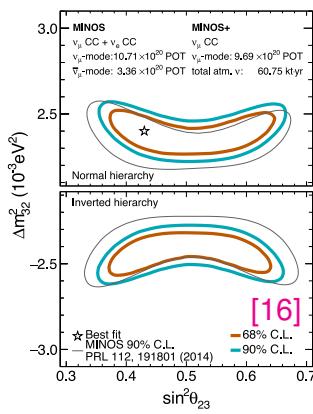
- Tension between **solar** and **KamLAND** related to:  $\left\{ \begin{array}{l} \text{-- too much D/N asymmetry in SK,} \\ \text{-- non-observation of low-E turn-up;} \end{array} \right.$
  - new SK data [13]: D/N asymmetry reduced ( $3.6\% \rightarrow 2.1\%$ ) and “hints” of turn-up.



[13] Y. Nakajima [SK], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

## Atmospheric oscillations: $\Delta m_{31}^2$ and $\theta_{23}$

- $\Delta m_{31}^2$  &  $\theta_{23}$  dominated by LBL disappearance ( $\nu_\mu \rightarrow \nu_\mu$ ) data;
- $\Delta m_{21}^2$  effects contribute only at subleading level;
- reasonably good agreement between all experiments in the allowed regions, although some small differences are visible.



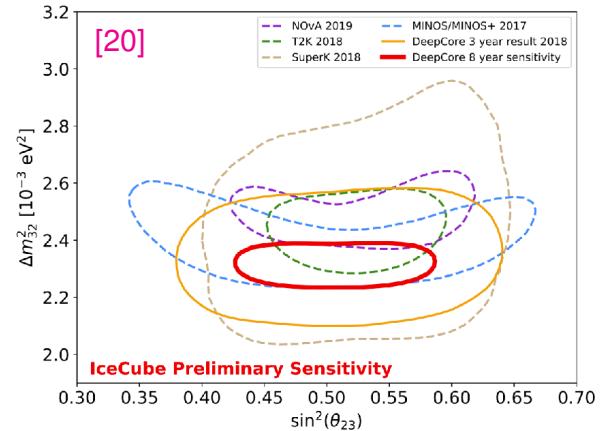
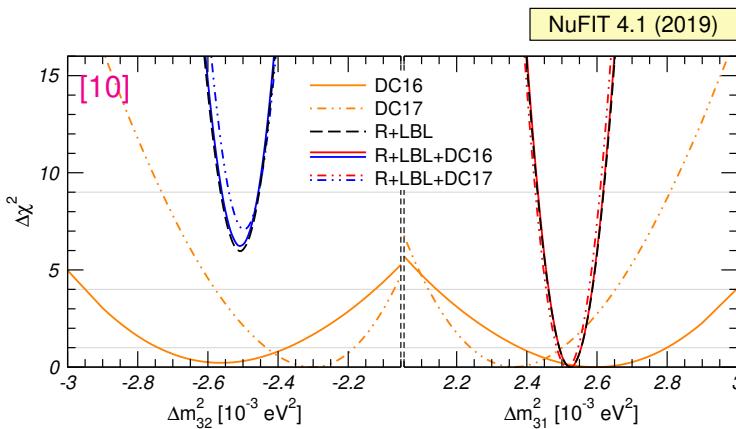
[14] P. Dunne [T2K], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

[15] A. Himmel [NOvA], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

[16] T. Carroll [MINOS], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

## The contribution of IceCUBE/DeepCore

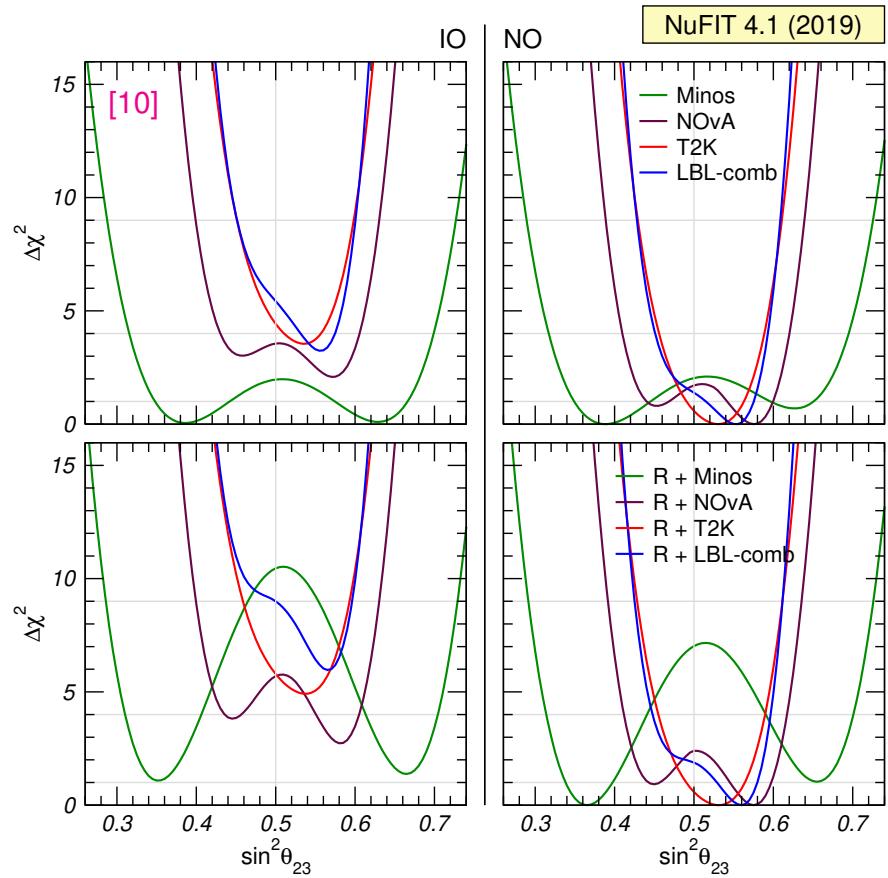
- Various analysis (DC16 [17], DC17 [18], DC19 [19]) of IceCUBE/DeepCore data have been presented, all based on three years of data (but **not** the same years);
- contribution to global fit still limited, but analysis with eight years is in progress [20].



- [10] I. Esteban *et al.*, JHEP **01** (2019) 106 [[arXiv:1811.05487](https://arxiv.org/abs/1811.05487)] & NuFIT 4.1 [<http://www.nu-fit.org>].
- [17] M.G. Aartsen *et al.* [DEEPCORE], PRD **91** (2015) 072004 [[arXiv:1410.7227](https://arxiv.org/abs/1410.7227)], updated Oct. 2016.
- [18] M.G. Aartsen *et al.* [DEEPCORE], PRL **120** (2018) 071801 [[arXiv:1707.07081](https://arxiv.org/abs/1707.07081)].
- [19] M.G. Aartsen *et al.* [DEEPCORE], PRD **99** (2019) 032007 [[arXiv:1901.05366](https://arxiv.org/abs/1901.05366)].
- [20] S. Blot [DEEPCORE], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

## $\theta_{23}$ mixing and octant

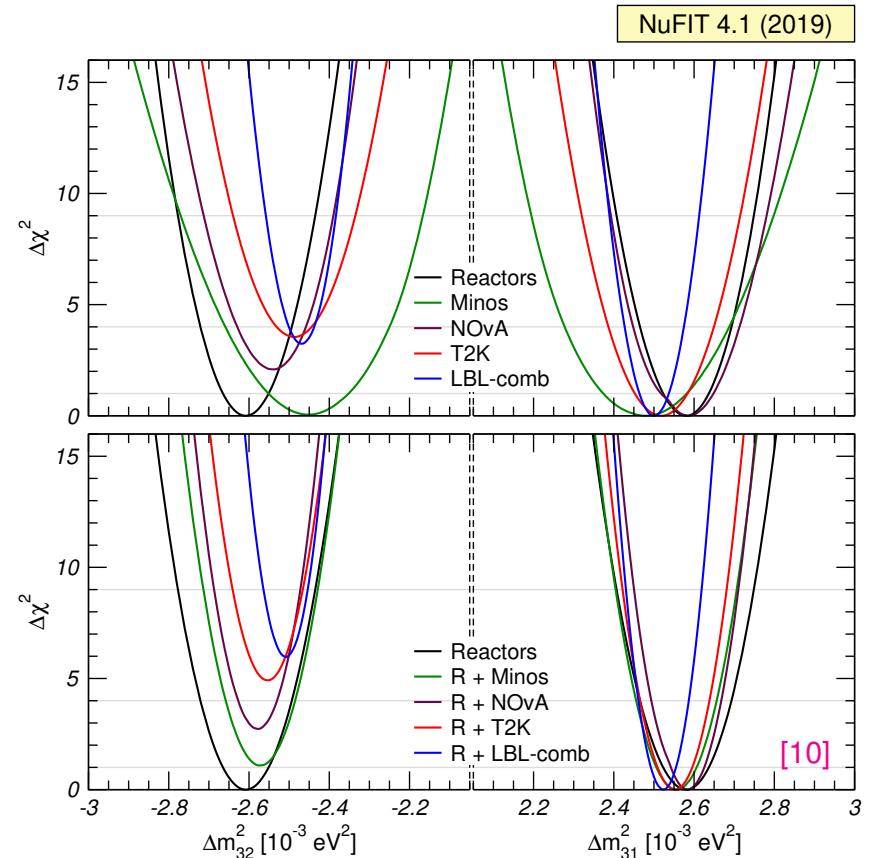
- Disappearance data:
  - T2K ( $\nu$  &  $\bar{\nu}$ ) and NOvA ( $\nu$ ) data favor maximal mixing;
  - NOvA ( $\bar{\nu}$ ) still favors non-maximal mixing, but significance is reduced since the previous release (2018);
  - Minos shows strongest deviation but lowest statistics;
- appearance data:
  - all experiments (except Minos) slightly favor  $\theta_{23} > 45^\circ$ ;
- similar results for NO and IO.



[10] I. Esteban et al., JHEP 01 (2019) 106 [arXiv:1811.05487] & NuFIT 4.1 [<http://www.nu-fit.org>].

## $\Delta m_{31}^2$ and mass ordering

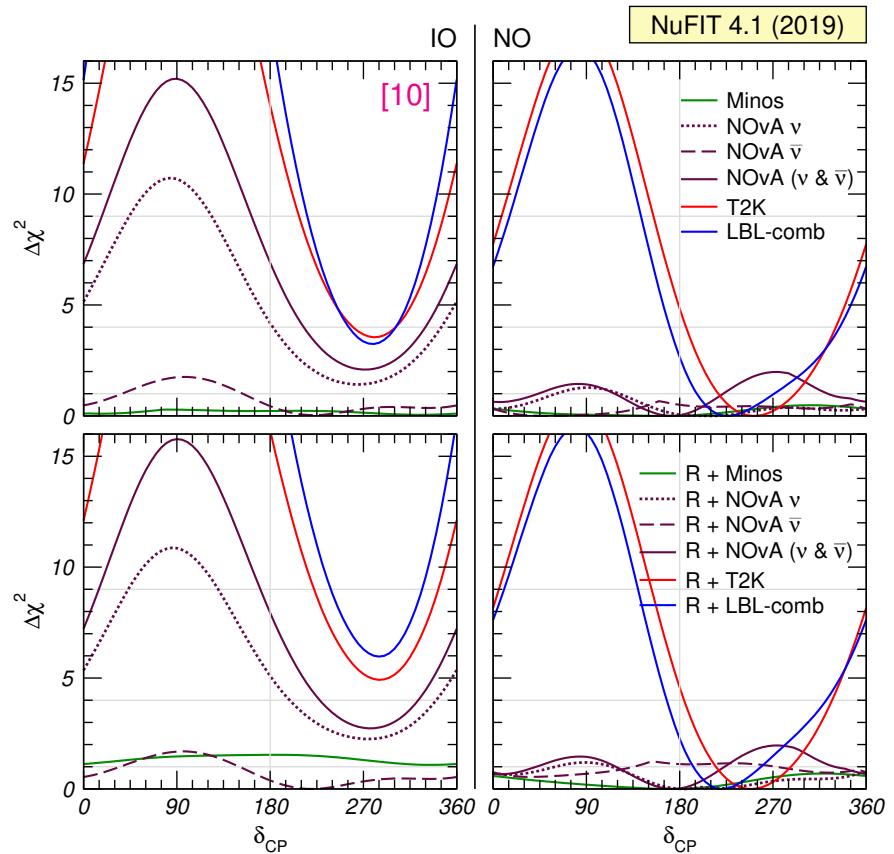
- All the LBL experiments exhibit a small preference for **NO** over **IO**, even when taken by themselves;
- such preference increases when they are combined with **reactors**, due to better agreement in the preferred  $\Delta m_{31}^2$  range;
- LBL preference for **NO** over **IO**:
  - $1.8\sigma$  (only  $\theta_{13}$  from reactors);
  - $2.4\sigma$  (full reactor info);
- inclusion of Super-K atmospheric data raises the significance to  $3.2\sigma$  ( $\Delta\chi^2 = 10.4$ ).



[10] I. Esteban *et al.*, JHEP 01 (2019) 106 [[arXiv:1811.05487](https://arxiv.org/abs/1811.05487)] & NuFIT 4.1 [<http://www.nu-fit.org>].

## Status of the CP phase

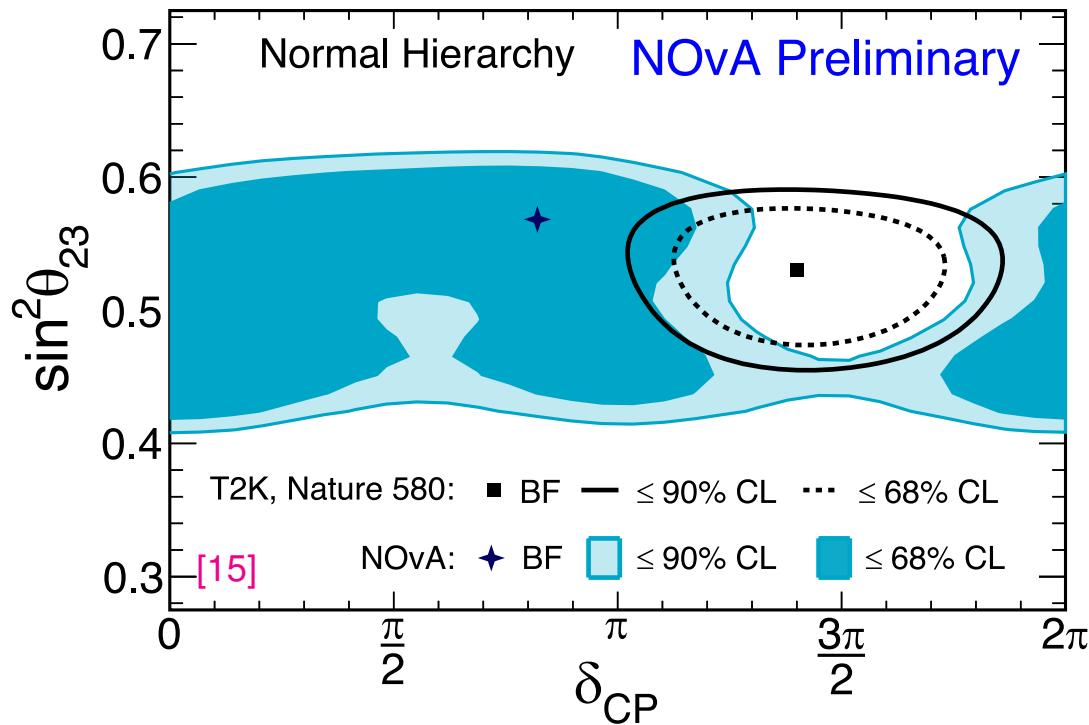
- T2K data show a clear preference for maximal CP violation ( $\delta_{CP} \simeq -\pi/2$ ), irrespective of the mass ordering;
- NOvA data also favor such value for **IO**, but for **NO** it disfavors it at  $1.5\sigma$ , preferring instead  $\delta_{CP} \simeq \pm\pi$  (CP-cons);
- Minos has practically no sensitivity to  $\delta_{CP}$ ;
- combined LBL experiments indicate  $\delta_{CP} \simeq -3\pi/4$ , midway between T2K and NOvA.



[10] I. Esteban et al., JHEP 01 (2019) 106 [arXiv:1811.05487] & NuFIT 4.1 [<http://www.nu-fit.org>].

**CP phase after Neutrino 2020 conference**

- Small tension between T2K and NOvA still present [15].



[15] A. Himmel [NOvA], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

## Neutrino oscillations: where we are

- Global 6-parameter fit (including  $\delta_{CP}$ ):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Bx;
  - **Atmospheric**: DeepCore;
  - **Reactor**: KamLAND + Dbl-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos + T2K + NOvA;

- best-fit point and  $1\sigma$  ( $3\sigma$ ) ranges:

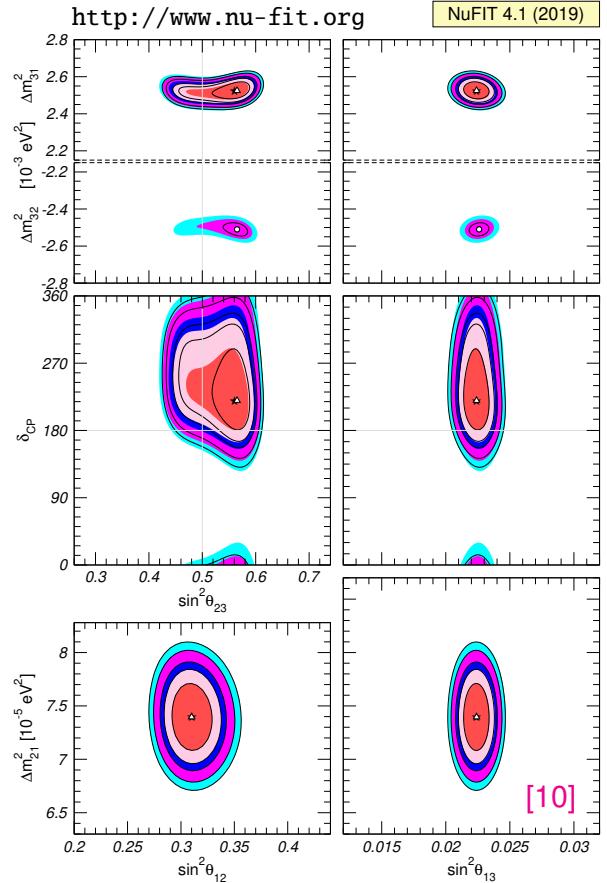
$$\theta_{12} = 33.82^{+0.78}_{-0.76} \left( {}^{+2.45}_{-2.21} \right), \quad \Delta m_{21}^2 = 7.39^{+0.21}_{-0.20} \left( {}^{+0.62}_{-0.60} \right) \times 10^{-5} \text{ eV}^2,$$

$$\theta_{23} = \begin{cases} 48.3^{+1.1}_{-1.9} \left( {}^{+3.0}_{-7.5} \right), \\ 48.6^{+1.1}_{-1.5} \left( {}^{+2.9}_{-7.6} \right), \end{cases} \quad \Delta m_{31}^2 = \begin{cases} +2.523^{+0.032}_{-0.030} \left( {}^{+0.095}_{-0.091} \right) \times 10^{-3} \text{ eV}^2, \\ -2.509^{+0.032}_{-0.030} \left( {}^{+0.093}_{-0.094} \right) \times 10^{-3} \text{ eV}^2, \end{cases}$$

$$\theta_{13} = 8.61^{+0.13}_{-0.13} \left( {}^{+0.38}_{-0.39} \right), \quad \delta_{CP} = 222^{+38}_{-28} \left( {}^{+148}_{-81} \right);$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.797 \rightarrow 0.842 & 0.518 \rightarrow 0.585 & 0.143 \rightarrow 0.156 \\ 0.244 \rightarrow 0.496 & 0.467 \rightarrow 0.678 & 0.646 \rightarrow 0.772 \\ 0.287 \rightarrow 0.525 & 0.488 \rightarrow 0.693 & 0.618 \rightarrow 0.749 \end{pmatrix}.$$



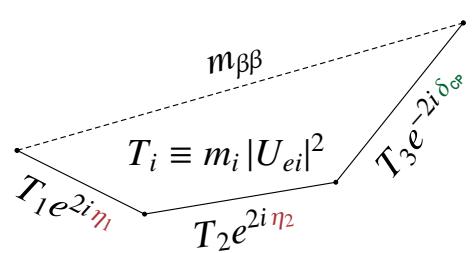
[10] I. Esteban *et al.*, JHEP 01 (2019) 106 [arXiv:1811.05487] & NuFIT 4.1 [<http://www.nu-fit.org>].

## Absolute neutrino mass scale and $0\nu\beta\beta$

- Quantities sensitive to absolute  $\nu$  masses:  $m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$  and  $m_{\beta\beta} = |\sum_i m_i U_{ei}^2|$ ;
- these new quantities depend on:
  - new parameters: lightest neutrino mass ( $m_0$ ) and Majorana phases ( $\eta_1$  and  $\eta_2$ );
  - oscillation parameters: mass-squared ( $\Delta m_{21}^2$ ,  $\Delta m_{31}^2$ ) and mixings ( $\theta_{12}$ ,  $\theta_{13}$ ,  $\delta_{CP}$ );
- notice that:
  - $\theta_{23}$  does not appear in  $U_{ei} \Rightarrow$  irrelevant for  $m_\beta$  and  $m_{\beta\beta}$ ;
  - only combinations ( $\delta_{CP} + \eta_i$ ) enter  $m_{\beta\beta} \Rightarrow$  specific  $\delta_{CP}$  value is not relevant;
- hence, phenomenological picture only affected by  $(\theta_{13}, \theta_{12}, \Delta m_{21}^2, \Delta m_{31}^2)$ .

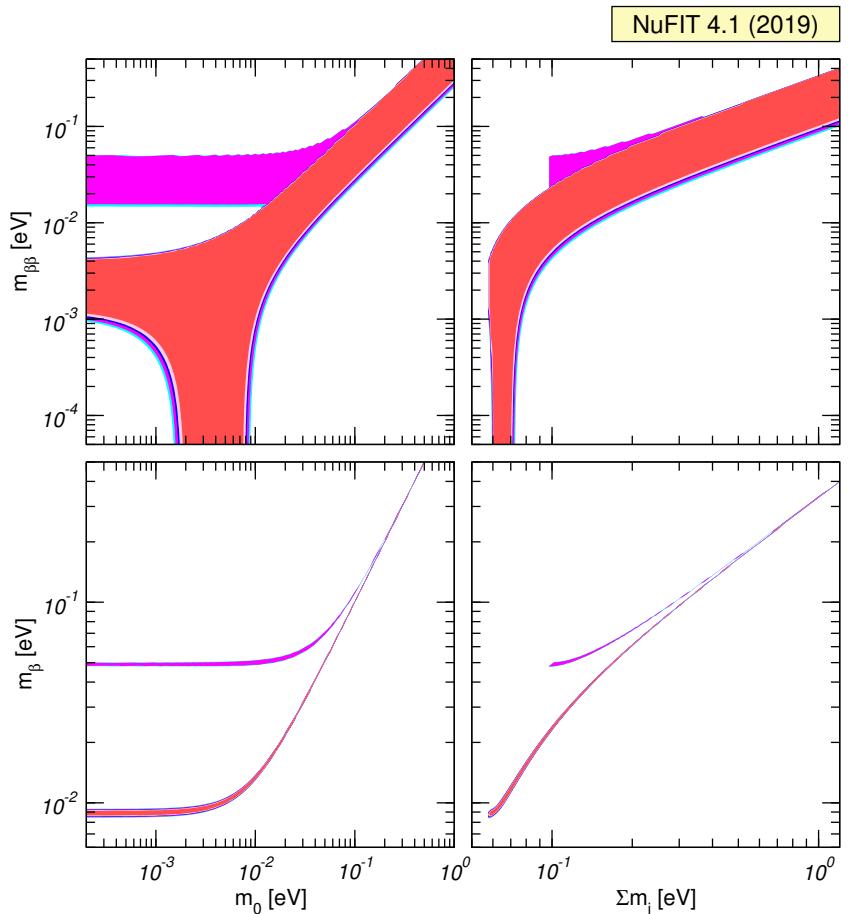
**NO:** 
$$\begin{cases} m_3^2 = m_1^2 + \Delta m_{31}^2 \\ m_2^2 = m_1^2 + \Delta m_{21}^2 \\ m_1^2 = m_0^2 \end{cases}$$

**IO:** 
$$\begin{cases} m_2^2 = m_3^2 + |\Delta m_{32}^2| \\ m_1^2 = m_2^2 - \Delta m_{21}^2 \\ m_3^2 = m_0^2 \end{cases}$$



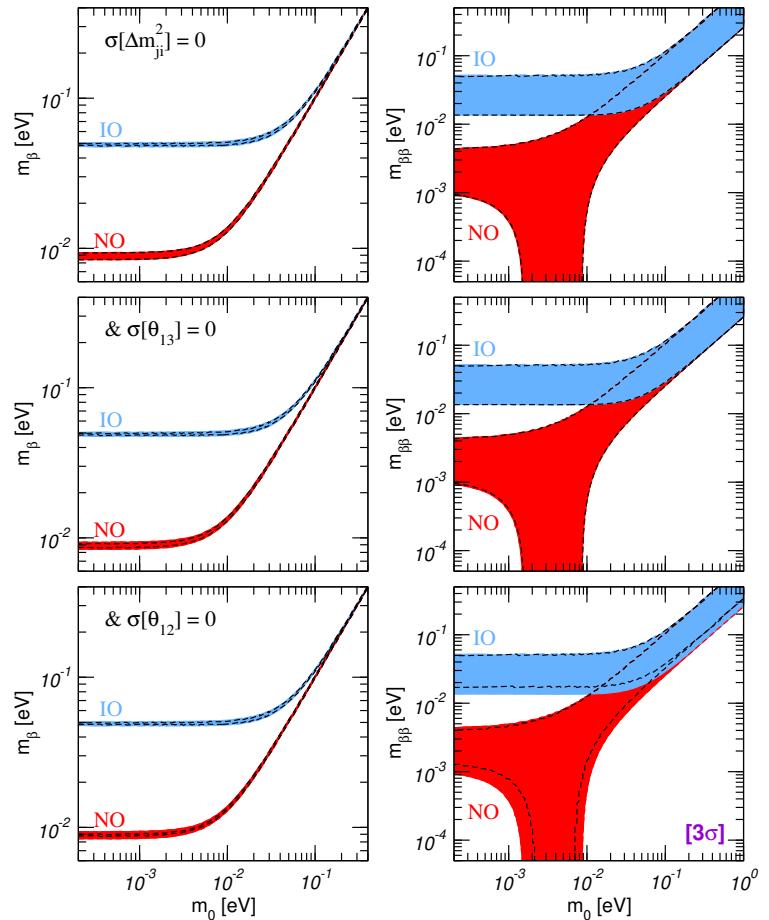
## Status of $m_\beta$ and $m_{\beta\beta}$

- Results of the global fit of oscillation data can be projected onto  $m_\beta$  and  $m_{\beta\beta}$  as a function of lightest  $\nu$  mass  $m_0$  (or  $\sum m_i$ );
- no neutrino ordering assumed: both cases considered on equal footing  $\Rightarrow$  IO region disfavored at  $\Delta\chi^2 = 6.2$  by oscillation data (growing to  $\Delta\chi^2 = 10.4$  if Super-K atmospheric data also included);
- extension of  $m_{\beta\beta}$  regions dominated by unknown  $\eta_i \Rightarrow$  flat  $\chi^2$  valley closed by steep walls  $\Rightarrow 1\sigma, 2\sigma, 3\sigma, \dots$  ranges very similar.

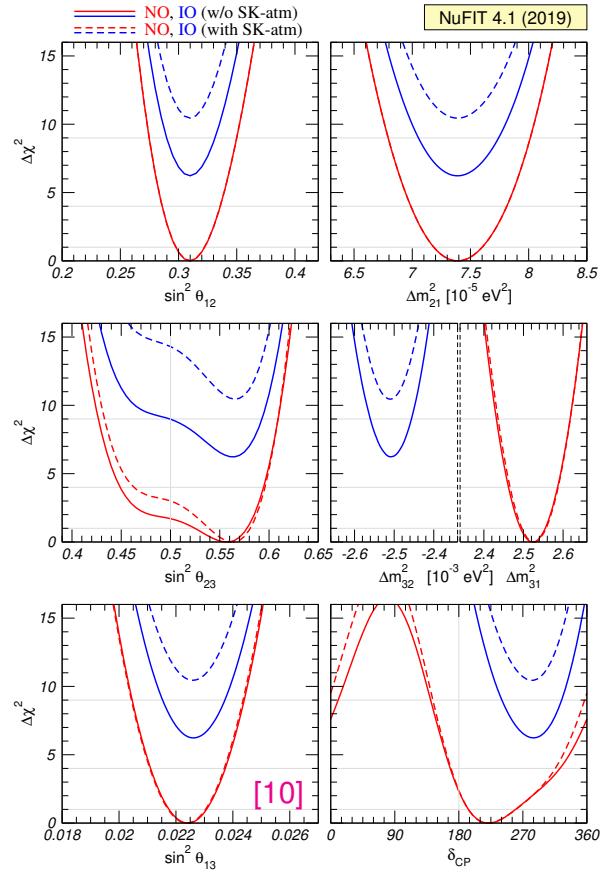


## Impact of osc. parameters

- Uncertainty on  $\Delta m_{21}^2$  and  $\Delta m_{31}^2$  has negligible impact on the extension of the  $m_\beta$  and  $m_{\beta\beta}$  regions;
  - uncertainty on  $\theta_{13}$  marginally affect  $m_\beta$ , and is irrelevant for  $m_{\beta\beta}$ ;
  - the only oscillation parameter whose precision has a visible (albeit small) impact on  $m_\beta$  and  $m_{\beta\beta}$  ranges is  $\theta_{12}$ ;
- ⇒ the present phenomenological picture will not be significantly affected by future improvements in the determination of the oscillation parameters, **except for what concerns the neutrino mass ordering.**



- Most of the present data from **solar**, **atmospheric**, **reactor** and **accelerator** experiments are well explained by the  $3\nu$  oscillation hypothesis. The three-neutrino scenario is robust;
- some interesting “hints” seem to be emerging for what concerns the **mass ordering**, with **NO** favored over **IO** at the  $2.4\sigma \div 3.2\sigma$  level (depending on the included data sets);
- the discovery of large  $\theta_{13}$  opened the road to searches for **CP violation**. However, results on this topic need further clarifications;
- deviation from **maximal  $\theta_{23}$  mixing** is also still an open issue.  $\theta_{23} > 45^\circ$  seems slightly preferred;
- synergies between different experiments will be crucial to increase the sensitivity.



[10] I. Esteban *et al.*, JHEP **01** (2019) 106 [[arXiv:1811.05487](https://arxiv.org/abs/1811.05487)] & NuFIT 4.1 [<http://www.nu-fit.org>].